Direct tests of $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ symmetries in transitions of neutral kaons at KLOE

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EPS-HEP - Hamburg, 21 August 2023

Neutral Kaons at the ϕ-factory

- Production and decay of neutral kaons at the ϕ-factory allows the researchers to test $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ symmetries by direct comparison of reference transitions between Kaon states with their symmetry-conjugate transitions

- Neutral Kaon pairs from ϕ decays have $J^{PC} = 1^{--}$

- A fully-antisymmetric quantum mechanics state is imposed by Bose statistics and angular momentum conservation preventing terms with identical bosons

$$|i> = \frac{1}{\sqrt{2}}\{|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\} = \frac{1}{\sqrt{2}}\{|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\}$$

- The maximal entanglement of meson-anti meson pairs is used to tag the initial state by the decay mode of the first-in-time kaon decay and to filter the final state according to the decay mode of the other

Testing $\mathcal{T}$, $\mathcal{CP}$ and $\mathcal{CPT}$

Comparison of transition rates between $\mathcal{CP}$ and flavour eigenstates recognised as genuine tests of $\mathcal{T}$, $\mathcal{CP}$ and $\mathcal{CPT}$ symmetries

[J. Bernabeu *et al.* *Nucl.Phys. B 868(2013)102, JHEP 10(2015)139*]

The decay of one kaon (first-in-time decay) identifies the initial state of the other Kaon, $K_2(0)$

Symmetry tested by the measurement of the transition rates $K_2(0) \to K_2(t)$

Example:

$K^0(0) \to K_{CP-}(t)$ compared with $K_{CP-}(0) \to K^0(t)$ for testing $\mathcal{T}$

$K^0(0)$ tagged by $K_1 \to \pi^+ e^- \bar{\nu}$

$K_{CP-}(t)$ filtered by $K_2 \to \pi^0\pi^0\pi^0$

$K_{CP-}(0)$ tagged by $K_1 \to \pi^+\pi^-$

$K^0(t)$ filtered by $K_2 \to \pi^- e^+ \nu$

compared with $\bar{K}^0(0) \to K_{CP-}(t)$ for testing $\mathcal{CP}$

$\bar{K}^0(0)$ tagged by $K_1 \to \pi^- e^+ \nu$

$K_{CP-}(t)$ filtered by $K_2 \to \pi^0\pi^0\pi^0$

compared with $K_{CP-}(0) \to \bar{K}^0(t)$ for testing $\mathcal{CPT}$

$K_{CP-}(0)$ tagged by $K_1 \to \pi^+\pi^-$

$\bar{K}^0(t)$ filtered by $K_2 \to \pi^+ e^- \bar{\nu}$

Ratio of Transition Rates

At KLOE we have measured transition rates from/to

K^0 and $\overline{K}^0$ flavour eigenstates to/from CP- eigenstates

$\mathcal{T}$ tests performed by the measurement of

$$R^{exp}_{2,T}(\Delta t) \equiv \frac{I(\pi^+ e^- \bar{\nu}, \pi^0\pi^0\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)} \quad \text{and} \quad R^{exp}_{4,T}(\Delta t) \equiv \frac{I(\pi^- e^+ \nu, \pi^0\pi^0\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$\mathcal{CP}$ tests:

$$R^{exp}_{2,CP}(\Delta t) \equiv \frac{I(\pi^+ e^- \bar{\nu}, \pi^0\pi^0\pi^0; \Delta t)}{I(\pi^- e^+ \nu, \pi^0\pi^0\pi^0; \Delta t)} \quad \text{and} \quad R^{exp}_{4,CP}(\Delta t) \equiv \frac{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$\mathcal{CPT}$ tests:

$$R^{exp}_{2,CPT}(\Delta t) \equiv \frac{I(\pi^+ e^- \bar{\nu}, \pi^0\pi^0\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)} \quad \text{and} \quad R^{exp}_{4,CPT}(\Delta t) \equiv \frac{I(\pi^- e^+ \nu, \pi^0\pi^0\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Measured the asymptotic values of the ratios, when $\Delta t \gg \tau_s$

Asymptotic values and Weisskopf-Wigner $\mathscr{H}$

$$\mathcal{N} \cdot R^{exp}_{2,T}(\Delta t \gg \tau_S) = 1 - 4\,\Re\epsilon + 4(\Re x_+ + \Re y)$$
$$\mathcal{N} \cdot R^{exp}_{4,T}(\Delta t \gg \tau_S) = 1 + 4\,\Re\epsilon + 4(\Re x_+ - \Re y)$$

$$R^{exp}_{2,CP}(\Delta t \gg \tau_S) = 1 - 4\,\Re\epsilon_S + 4(\Re y - \Re x_-)$$
$$R^{exp}_{4,CP}(\Delta t \gg \tau_S) = 1 + 4\,\Re\epsilon_L - 4(\Re y + \Re x_-)$$

$$\mathcal{N} \cdot R^{exp}_{2,CPT}(\Delta t \gg \tau_S) = 1 - 4\,\Re\delta + 4(\Re x_+ - \Re x_-)$$
$$\mathcal{N} \cdot R^{exp}_{4,CPT}(\Delta t \gg \tau_S) = 1 + 4\,\Re\delta + 4(\Re x_+ + \Re x_-)$$

with $\mathcal{N} = \dfrac{BR(K_S \to \pi^+\pi^-) \cdot \Gamma_S}{BR(K_L \to \pi^0\pi^0\pi^0) \cdot \Gamma_L}$

$\mathcal{T}$, $\mathcal{CP}$ and $\mathcal{CPT}$ tests under the assumptions of

- validity of the $\Delta S = \Delta Q$ rule
- CPT invariance in semileptonic decay amplitudes (for $\mathcal{T}$ and $\mathcal{CP}$ tests)
- No direct CP and CPT violation in $\pi\pi$ and $\pi\pi\pi$ decay amplitudes

If all violation effects are those in the Weisskopf-Wigner Hamiltonian terms in brackets show possible spurious effects when assumptions are released

Direct CP violation in the decays does not affect the validity of the tests being completely negligible **[J. Bernabeu *et al. Nucl.Phys. B868(2013)102, JHEP 10(2015)139*]**

Double Ratio of Transition Rates

$$DR_{T,CP} \equiv \frac{R^{exp}_{2,T}(\Delta t \gg \tau_S)}{R^{exp}_{4,T}(\Delta t \gg \tau_S)} = \frac{R^{exp}_{2,CP}(\Delta t \gg \tau_S)}{R^{exp}_{4,CP}(\Delta t \gg \tau_S)} = 1 - 8\,\Re\epsilon + 8\,(\Re y)$$

$y \rightarrow$ CPT violation in $\Delta S = \Delta Q$ transitions

$$DR_{CPT} \equiv \frac{R^{exp}_{2,CPT}(\Delta t \gg \tau_S)}{R^{exp}_{4,CPT}(\Delta t \gg \tau_S)} = 1 - 8\,\Re\delta - 8\,(\Re x_{-})$$

$x_{-} \rightarrow$ CPT violation in $\Delta S \neq \Delta Q$ transitions

Data Analysis

Decay chains $\Phi \to K_1^0 K_2^0 \to \pi^\pm e^\mp \nu \;\; \pi^0\pi^0\pi^0$ and $\Phi \to K_1^0 K_2^0 \to \pi^+\pi^- \;\; \pi^\pm e^\mp \nu$ have been selected

All best features of the KLOE detectors exploited

DC Momentum resolution, $\dfrac{\Delta p_\perp}{p_\perp} \simeq 0.4\,\%$

Calorimeter Time resolution, $\Delta T \simeq \dfrac{54\ ps}{\sqrt{E\,[GeV]}}$

$\Phi \to K_1^0 K_2^0 \to \pi^\pm e^\mp \nu \;\; \pi^0\pi^0\pi^0$ selection: challenging $K_1^0 \to \pi^+\pi^-$ rejection

$\Phi \to K_1^0 K_2^0 \to \pi^+\pi^- \;\; \pi^\pm e^\mp \nu$ selection: easier, major point is $K_2^0 \to \pi^+\pi^-\pi^0$ and $K_2^0 \to \pi\mu\nu$ rejection

Semileptonic decays: Particle and charge ID

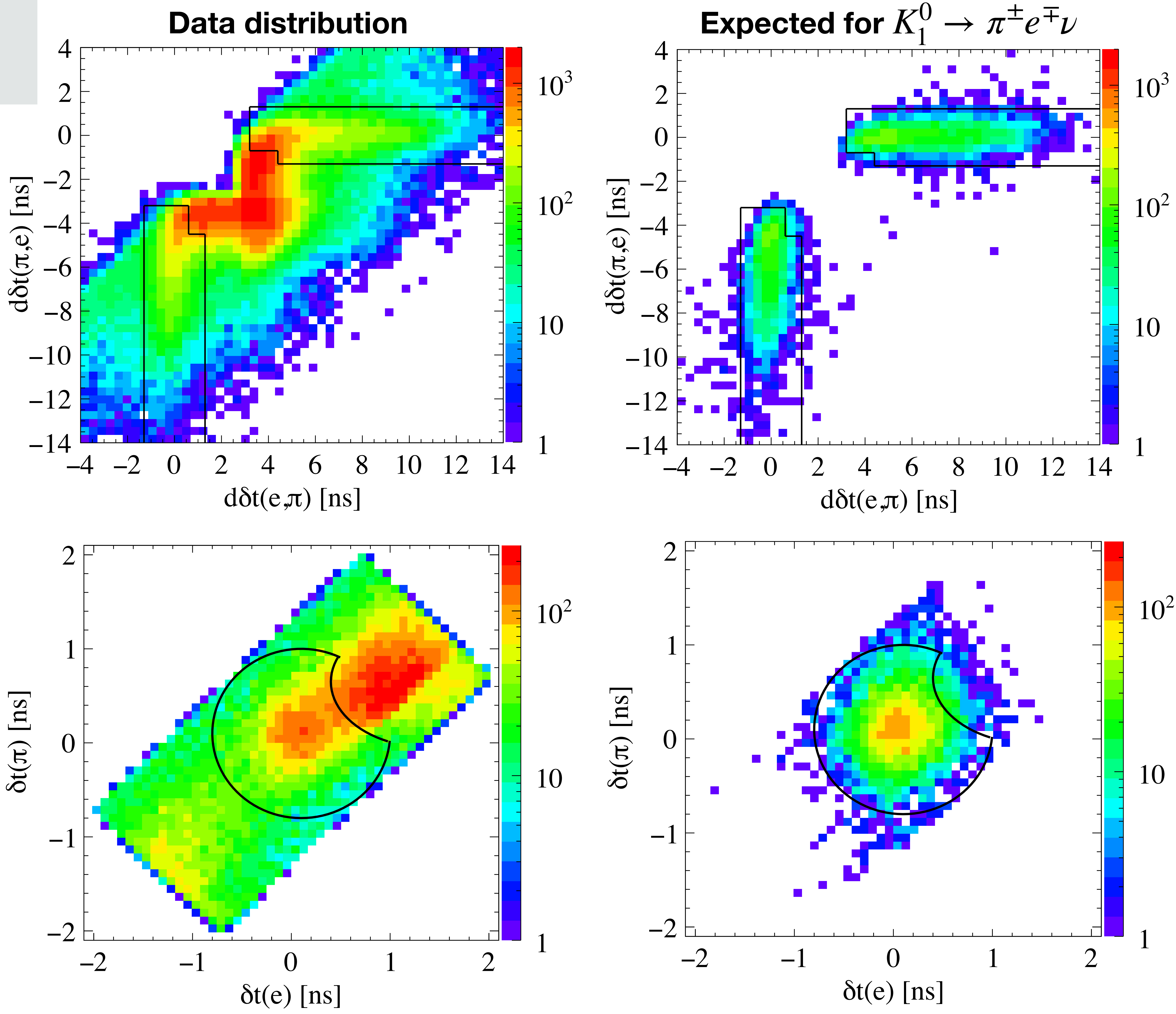
Charged tracks must arrive to the calorimeter

Calorimeter time compared with time of flight (TOF) from particle tracking in the DC for different mass hypothesis (m_π and m_e)

$$\delta t_i(m_1) = T_i - \frac{L_i}{c\,p_i}\sqrt{p_i^2 + m_1^2}$$

For the two-particles:

$$d\delta t(m_1, m_2) = \delta t_1(m_1) - \delta t_2(m_2)$$



$\pi^{\pm}e^{\mp}\nu$ $\pi^0\pi^0\pi^0$ selection

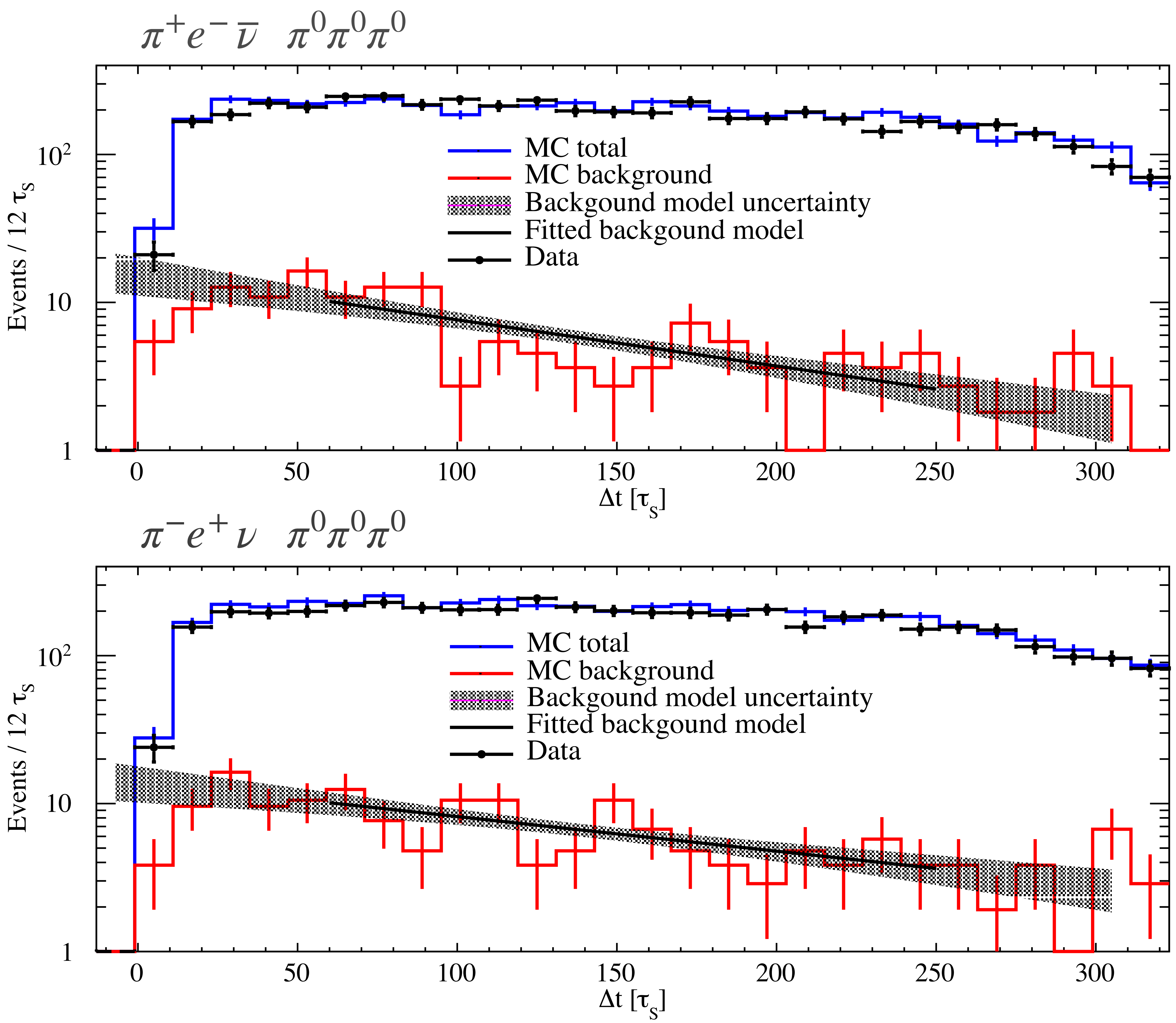
$\pi^0\pi^0\pi^0$ decays : 6 neutral clusters in the calorimeter + loose cut on TOF to reduce background from $K_S \to \pi^0\pi^0$

Remaining background from e/π and e/μ misidentification

ANN classifier trained with shapes of the clusters associated to the tracks in the DC to reduce the residual background

S/B ratios of 22.5 achieved

Background dependence from Δt studied, modelled and subtracted



$\pi^+\pi^- \quad \pi^\pm e^\mp \nu$ selection

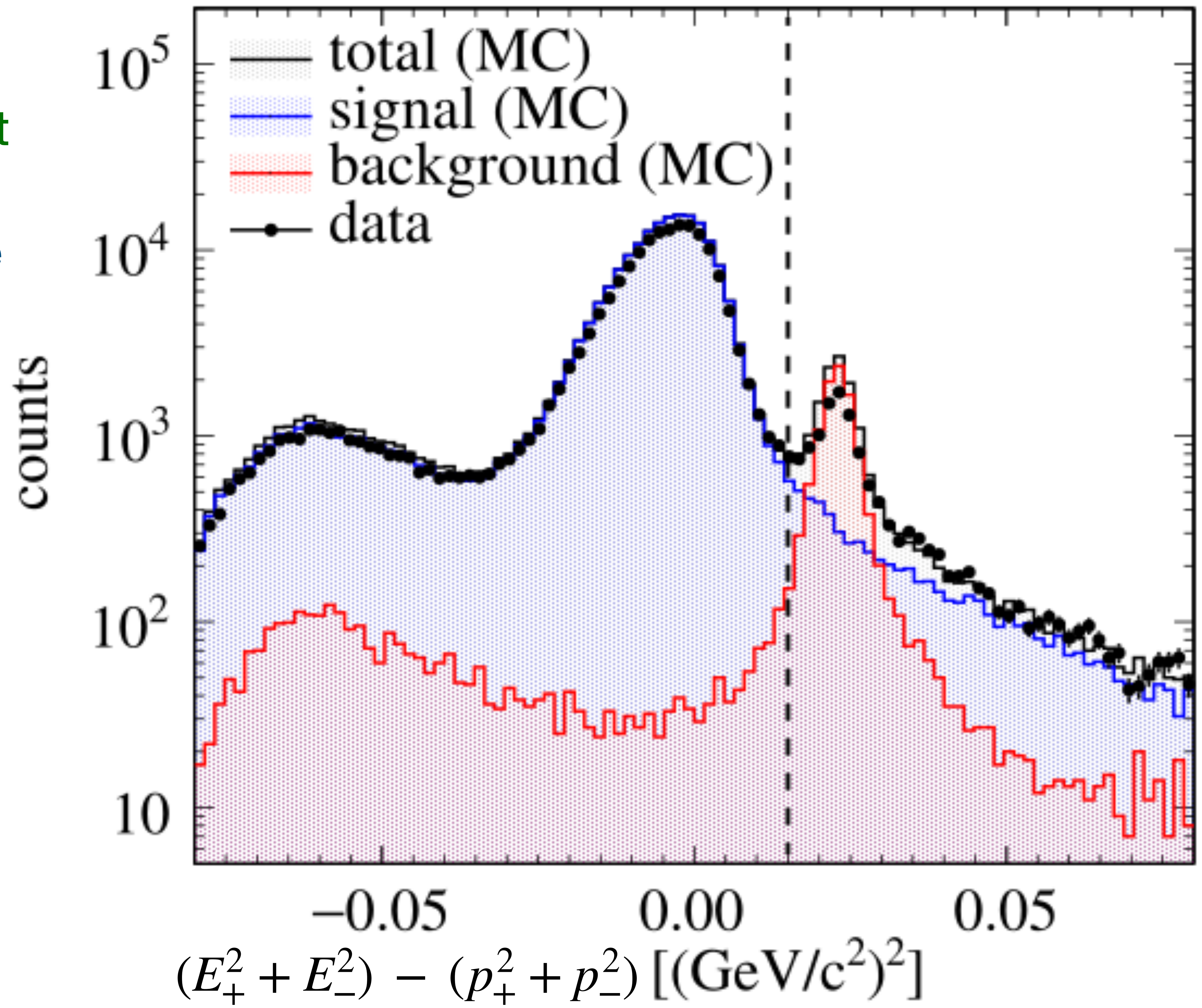
Vertex reconstruction @ IP and $m_{\pi^+\pi^-}$ invariant mass cut

Vertex reconstruction from other 2 tracks with opposite curvature in the DC

Signal/Background discrimination using $E_\pm = E_K - E(\pi_\mp) - p_{miss}$ and

$(E_+^2 + E_-^2) - (p_+^2 + p_-^2) < 0.015$ (GeV/c^2)^2

S/B ratio of 75 achieved



Efficiency evaluation

$\epsilon(\Delta t) = \epsilon_{TEC} \cdot \epsilon_{SEL}(\Delta t)$ is the product of trigger and event preselection filters, ϵ_{TEC}, independent from the decay lenghts, and the efficiency of the event selection, $\epsilon_{SEL}(\Delta t)$

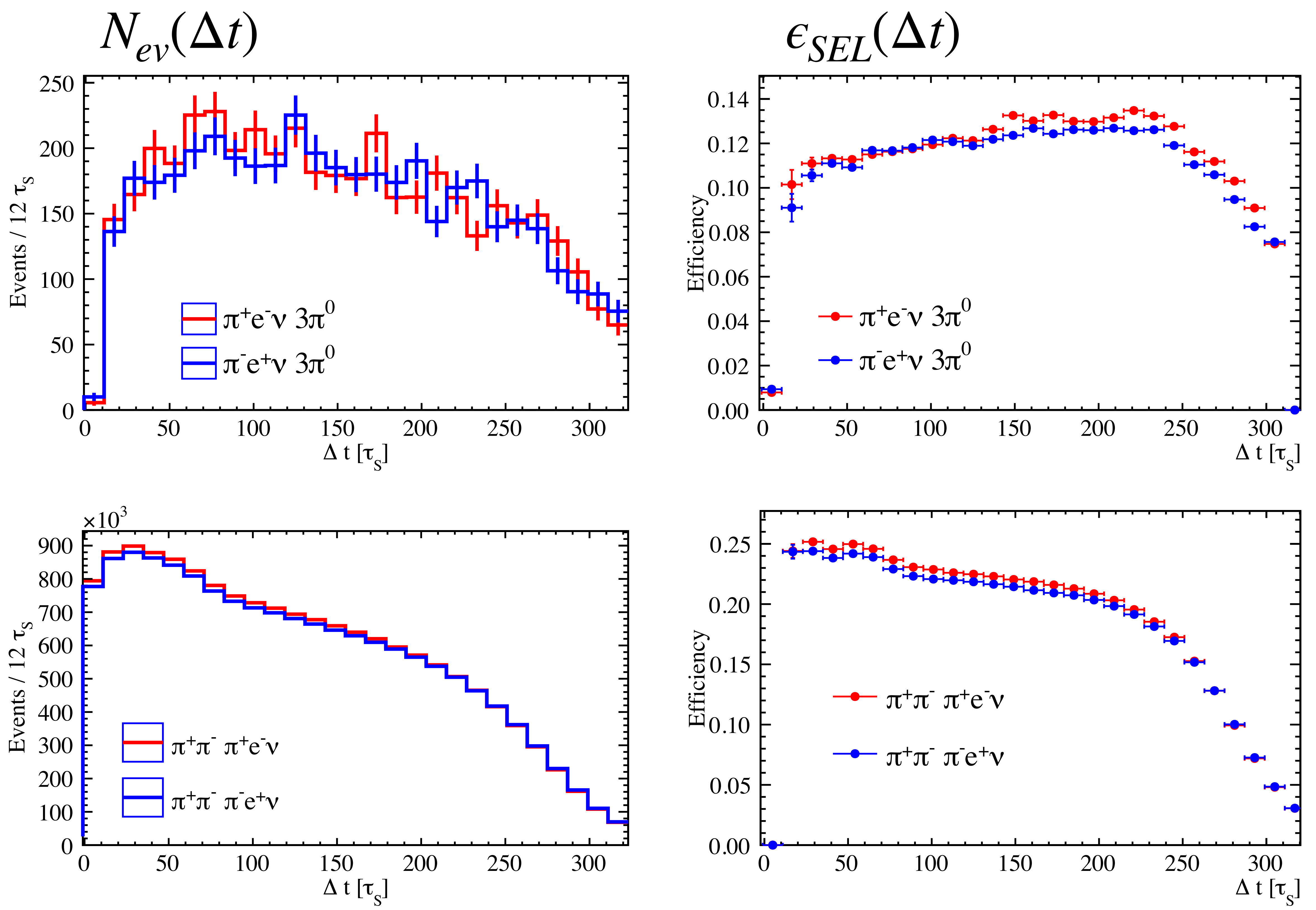
	$\epsilon_{TEC}[\,\%\,]$
$\pi^+e^-\bar{\nu}\ \ \pi^0\pi^0\pi^0$	99.49 ± 0.07
$\pi^-e^+\nu\ \ \pi^0\pi^0\pi^0$	99.45 ± 0.07
$\pi^+\pi^-\ \ \pi^+e^-\bar{\nu}$	99.60 ± 0.01
$\pi^+\pi^-\ \ \pi^-e^+\nu$	99.60 ± 0.01

$\epsilon_{SEL}(\Delta t)$ is evaluated by MonteCarlo corrected by the analysis of independent control samples

$\Phi \to K_1^0 K_2^0 \to \pi^0\pi^0\ \pi^\pm e^\mp \nu\,,\ \Phi \to K_1^0 K_2^0 \to \pi^\pm e^\mp \nu\ K_{CalIn}$

$\Phi \to K_1^0 K_2^0 \to \pi^+\pi^-\ \pi^0\pi^0\pi^0\,,\ \Phi \to K_1^0 K_2^0 \to \pi^+\pi^-\ K_{CalIn}$

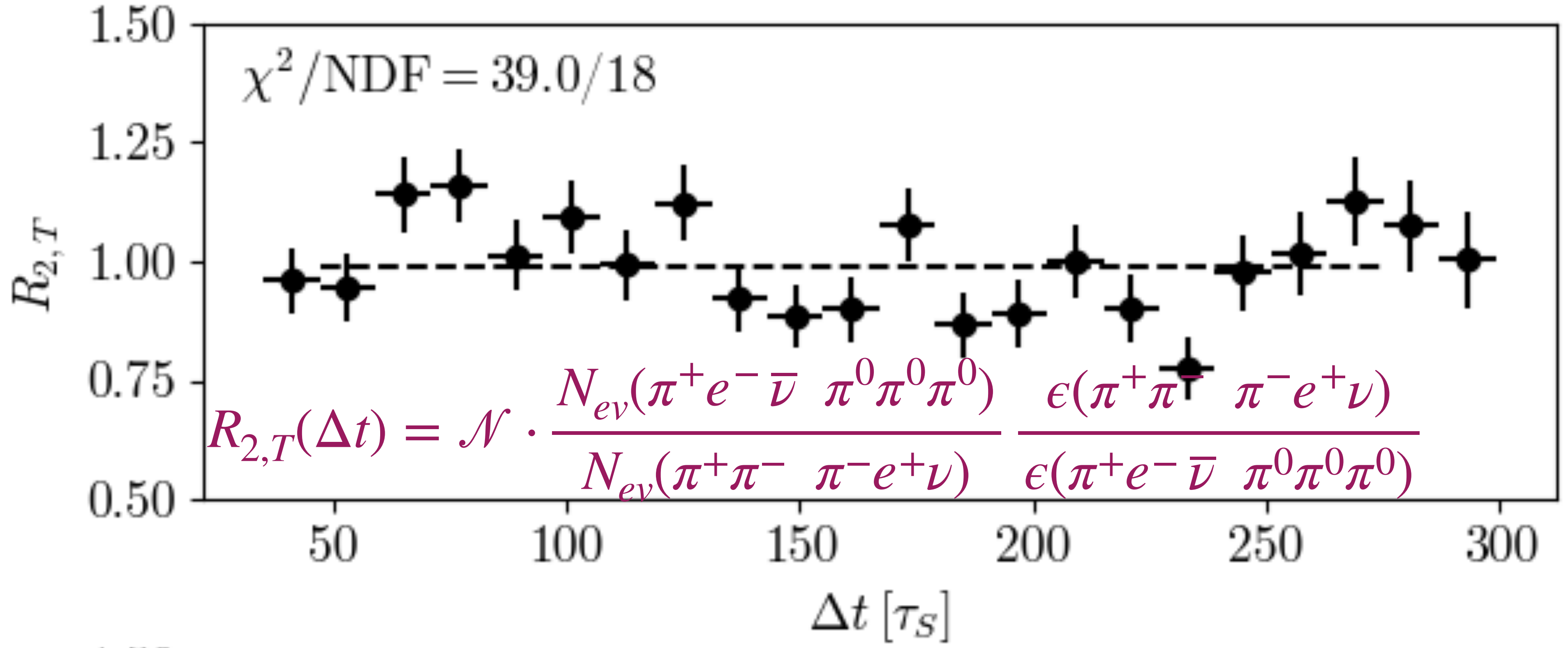
used to evaluate Data/MonteCarlo correction

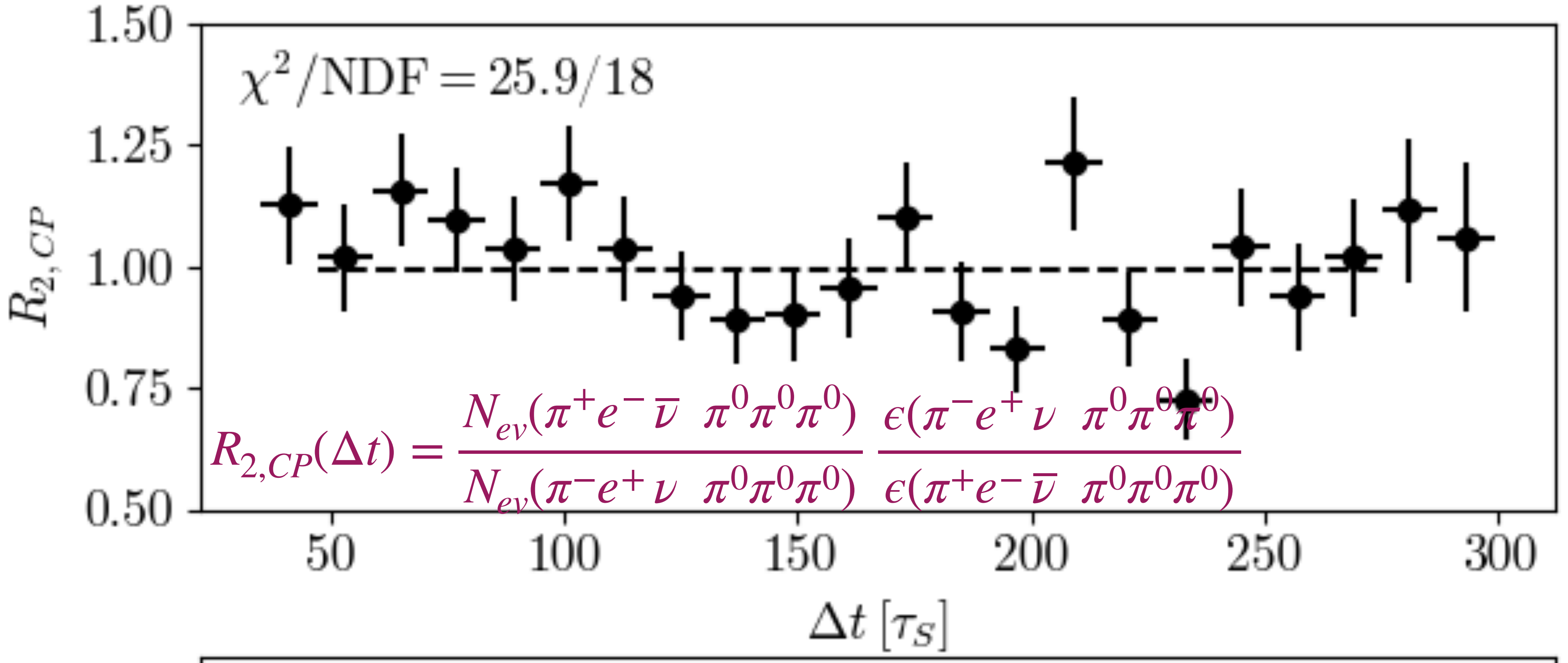


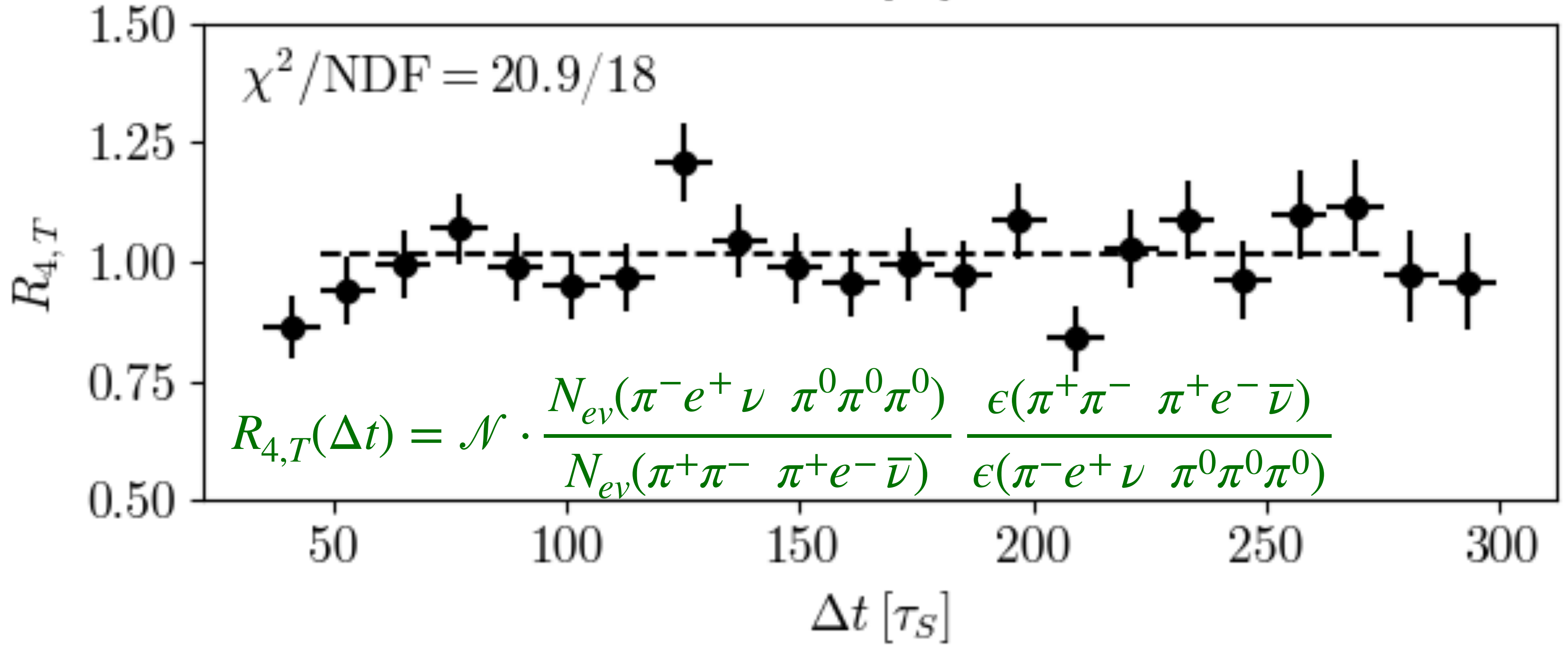
Testing $\mathcal{T}$, CP

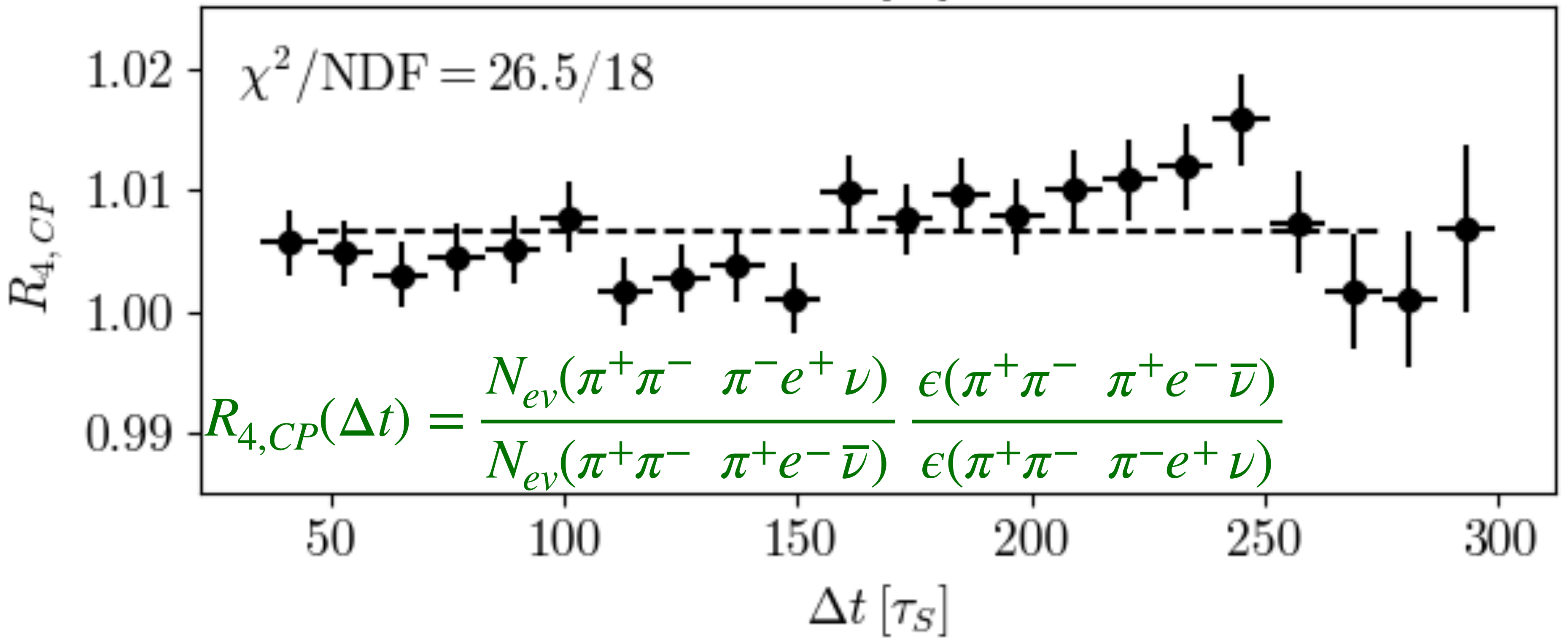
	events
$\pi^+e^-\bar{\nu}\ \ \pi^0\pi^0\pi^0$	4750
$\pi^-e^+\nu\ \ \pi^0\pi^0\pi^0$	4652
$\pi^+\pi^-\ \ \pi^+e^-\bar{\nu}$	15924863
$\pi^+\pi^-\ \ \pi^-e^+\nu$	15708190

$$\mathcal{N} = \frac{BR(K_S \to \pi^+\pi^-)\cdot\Gamma_S}{BR(K_L \to \pi^0\pi^0\pi^0)\cdot\Gamma_L} = (1.970 \pm 0.023)\ 10^3$$

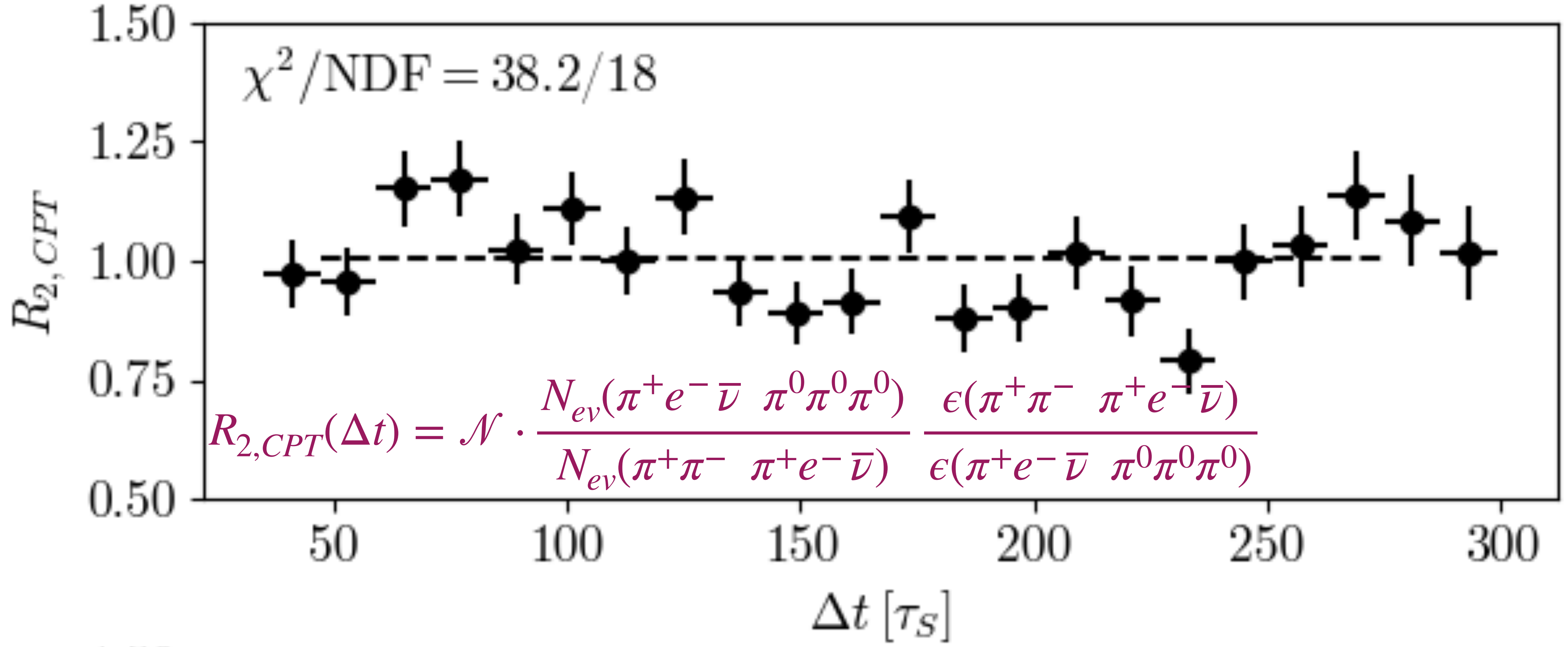


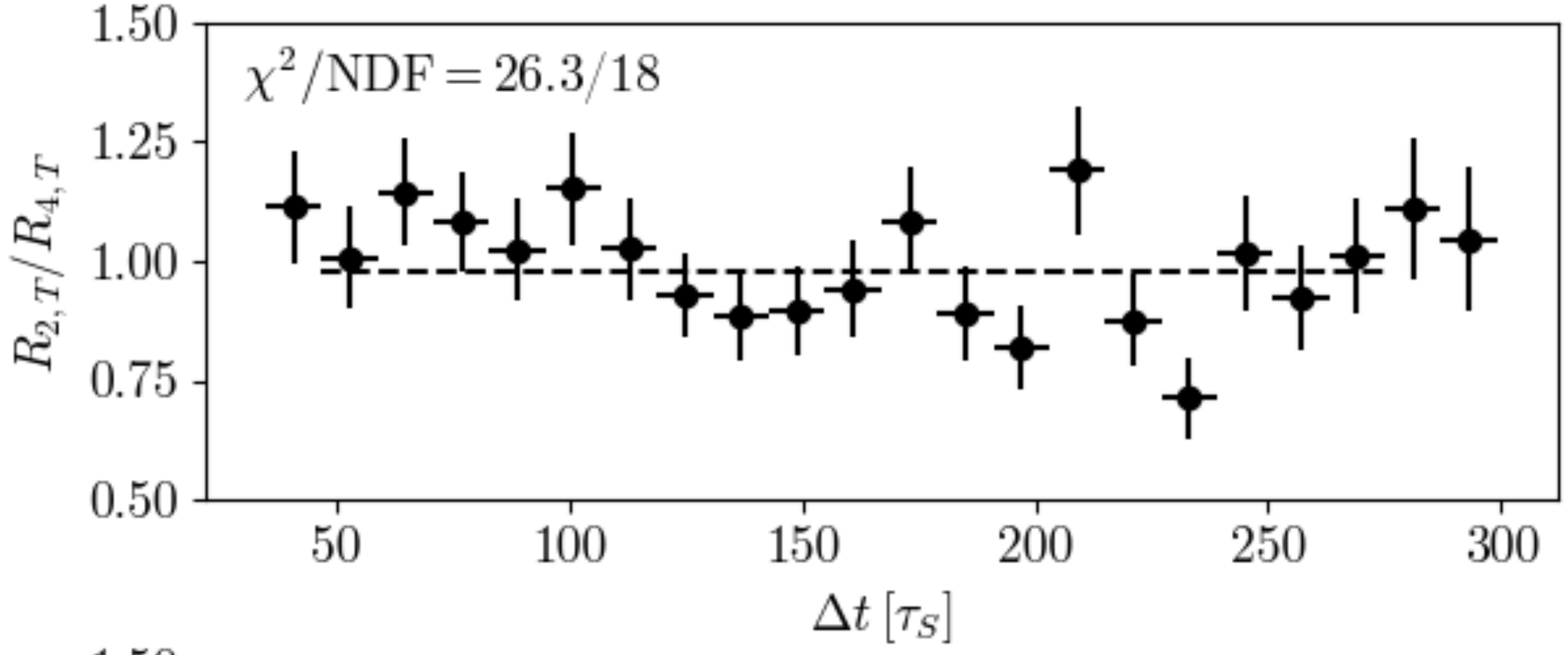


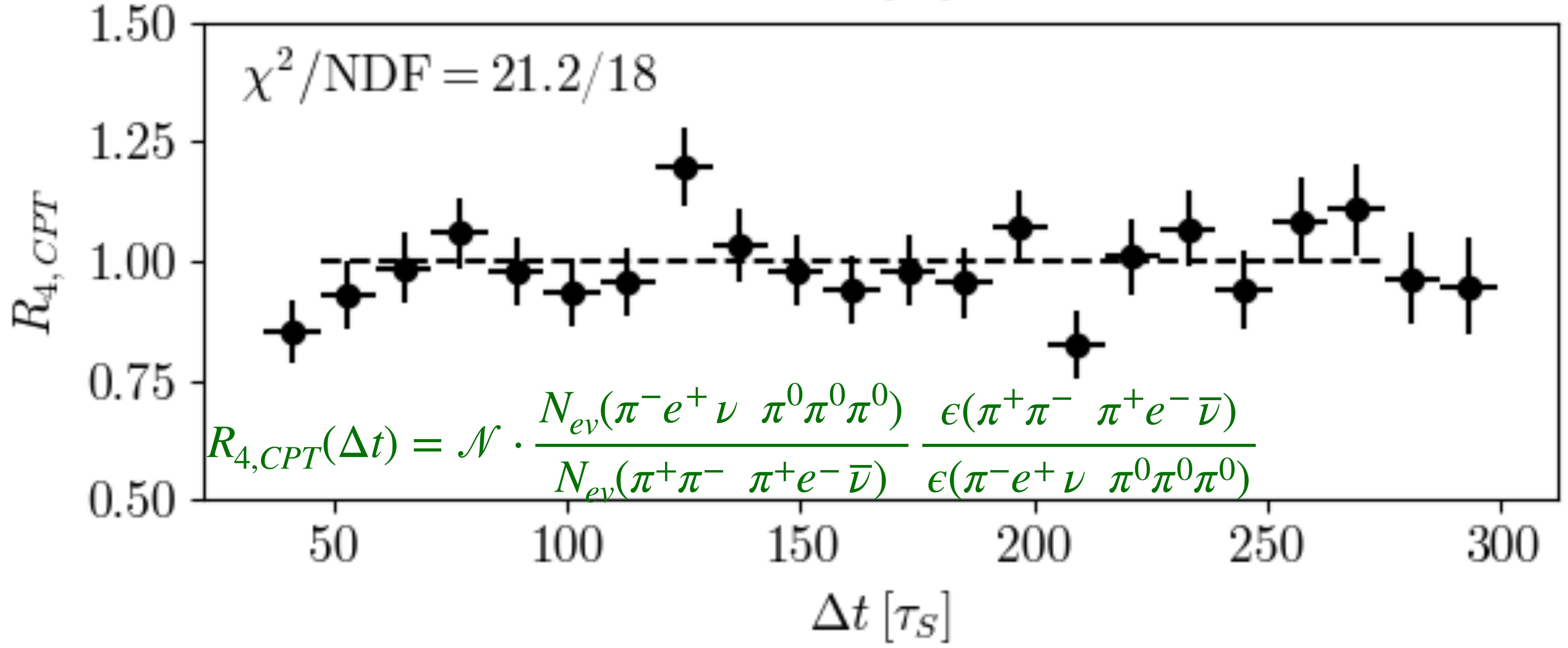


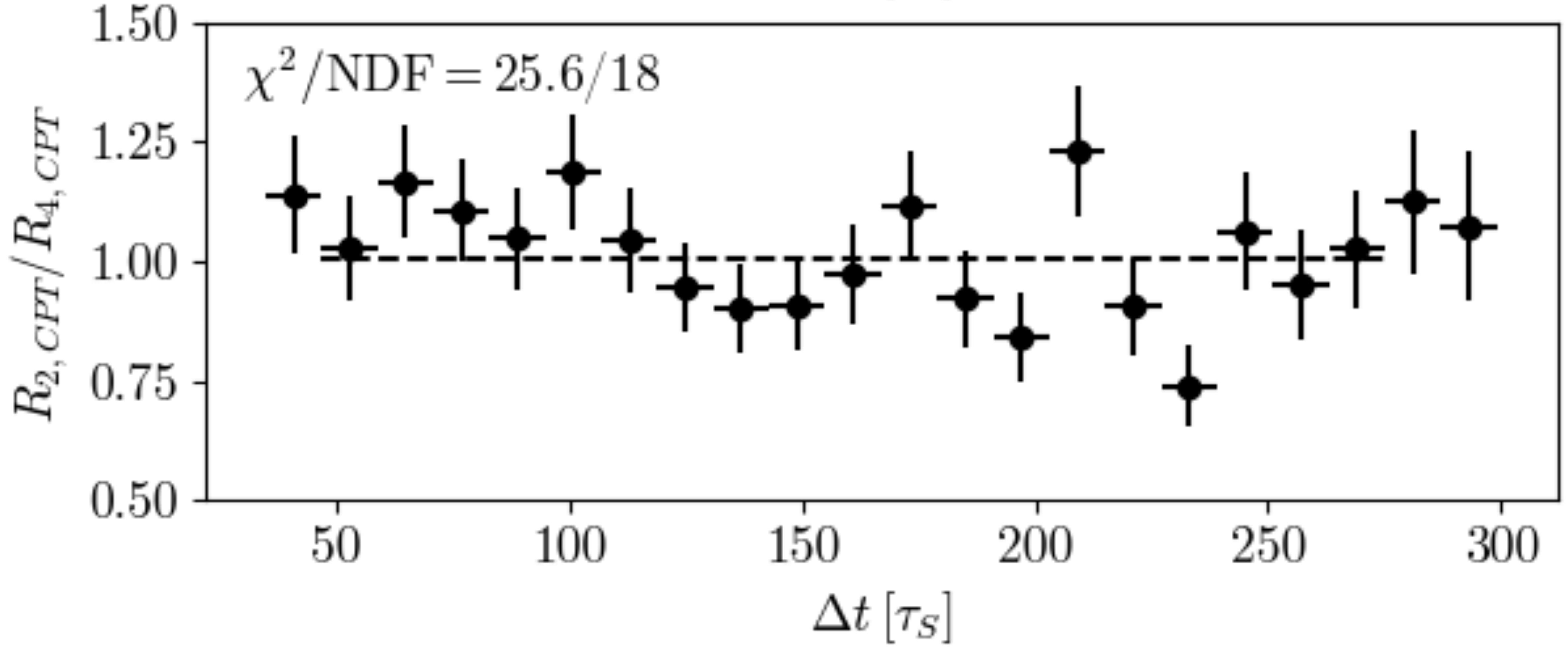


Testing $\mathcal{CPT}$ and Double Ratios









Systematics

Effect	$R_{2,T}$ $\times 10^{-3}$	$R_{4,T}$ $\times 10^{-3}$	$R_{2,CPT}$ $\times 10^{-3}$	$R_{4,CPT}$ $\times 10^{-3}$	$DR_{T,CP}$ $\times 10^{-3}$	DR_{CPT} $\times 10^{-3}$	$R_{2,CP}$ $\times 10^{-3}$	$R_{4,CP}$ $\times 10^{-3}$
Background model	2.74	4.62	2.79	4.43	4.43	4.41	4.37	–
Efficiency smoothing	2.46	5.31	2.43	5.26	6.70	6.83	6.76	0.17
Δt bin width	8.00	5.00	7.50	5.50	9.00	9.00	8.90	0.03
Fit range	7.33	8.88	7.32	8.84	7.95	7.60	7.78	0.41
Effects of cuts in the $(\pi e\nu)(3\pi^0)$ selection								
K_S vertex location cuts	0.57	2.31	0.58	2.27	2.36	2.41	2.39	–
$M(\pi,\pi)$ cut	2.48	1.34	2.52	1.31	1.56	1.63	1.60	–
TOF cuts	6.08	5.32	6.19	5.23	6.40	6.58	6.49	–
$e/\pi/\mu$ classification	4.78	4.40	4.85	4.33	9.33	9.59	9.46	–
Effects of cuts in the $(\pi^+\pi^-)(\pi e\nu)$ selection								
K_S vertex location cuts	0.007	0.004	0.004	0.007	0.004	0.004	–	0.005
$M(\pi,\pi)$ and $\lvert\vec{p}\rvert$ cuts	2.14	1.68	1.67	2.17	0.70	0.72	–	0.74
$m_+^2 + m_-^2$ cut	1.48	1.32	1.31	1.49	0.20	0.21	–	0.21
TOF cuts	2.14	1.68	1.67	2.17	0.70	0.72	–	0.74
Total systematic uncertainty	**14**	**15**	**14**	**15**	**19**	**19**	**19**	**0.89**
D factor total uncertainty	12	12	12	12	–	–	–	–

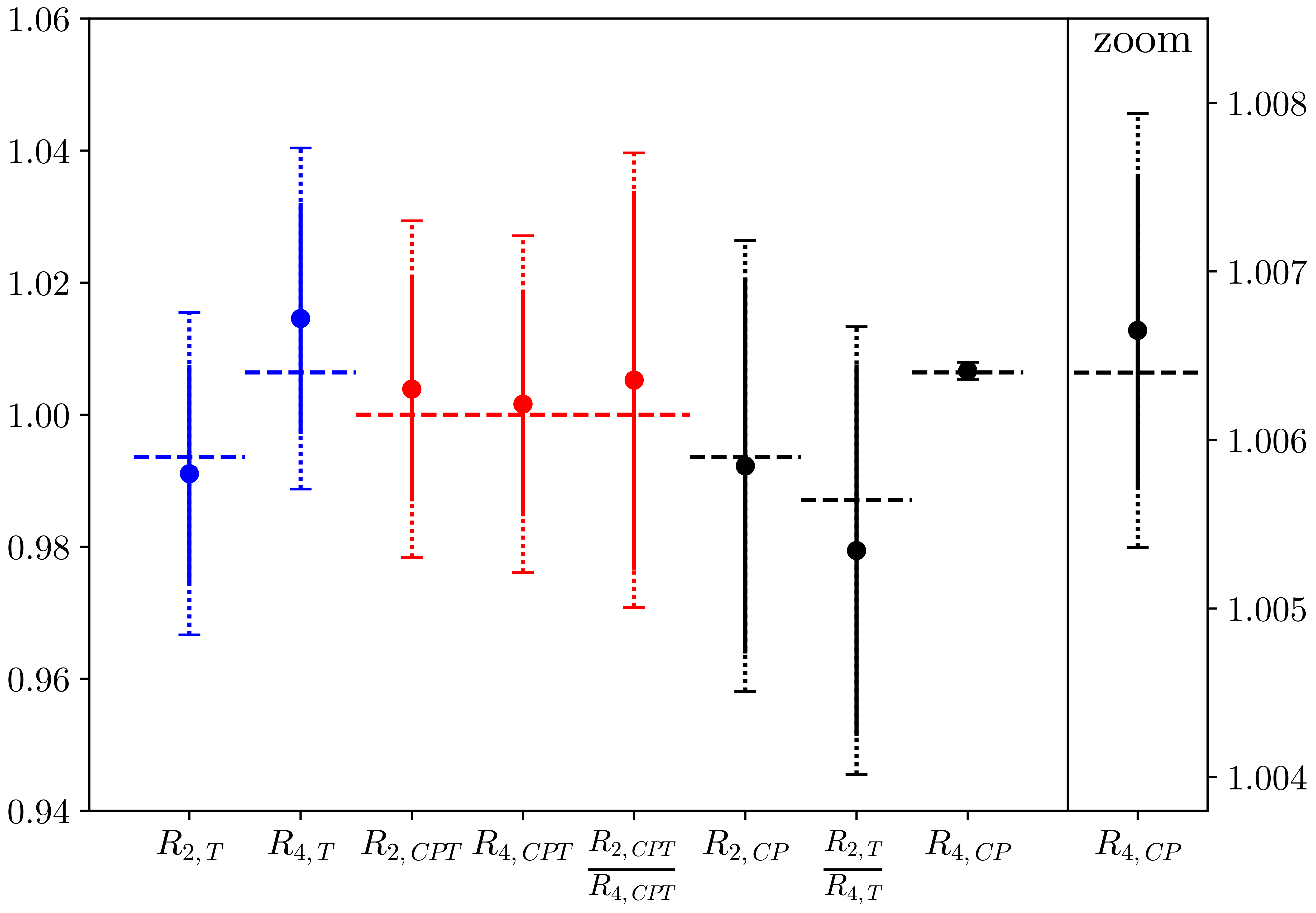
Summary

Asymptotic value of the ratios obtained by a fit in the region $\Delta t \in (47,275)\tau_S$ with bin width of $12\tau_S$

Fit errors on the ratios probing $\mathcal{T}$, $\mathcal{CPT}$ invariance at 1.7% level

The result for the double ratio testing $\mathcal{CPT}$ invariance is $DR_{CPT} = 1.005 \pm 0.029_{stat} \pm 0.019_{syst}$

For the CP test, with 16 M events in each charge of the semileptonic decay, we obtain:
$R_{4,CP} = 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst}$,
with 0.13% relative error



Conclusions

Kaon semileptonic decays with charge ID, in association with $\pi^+\pi^-$ or $\pi^0\pi^0\pi^0$ decays have been analyzed by the KLOE experiment at the Φ-factory, on the basis of 1.7 fb^{-1} of integrated luminosity

Direct tests of $\mathcal{T}$, $\mathcal{CPT}$ invariance at $3\ \%$ level of sensitivity have been performed

Statistical Sensitivity is at the level of Systematics

The first observation of CP violation in $K_- \rightarrow K^0/\ \overline{K}^0$ transitions with 5.2σ significance is obtained, being $R_{4,CP} = 1.00665\ \pm\ 0.00093_{stat}\ \pm\ 0.00089_{syst}$ with $0.13\ \%$ relative error, in agreement with previous results from $K^0/\ \overline{K}^0 \rightarrow K_+$ transitions